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Improving road ice prediction models
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Objective method for improving the operational performance of a road ice prediction model using interpolated mesoscale output and a templet for correcting systematic error

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Summary

Two techniques for improving the operational performance of numerical road ice prediction models are presented. The first uses the output from a mesoscale model to estimate the inputs for site-specific forecasts. The second uses a templet to reduce systematic bias in model output.

1. Introduction

The Meteorological Office numerical road ice prediction model (MORIPM) is now widely used in the United Kingdom to produce OpenRoad forecasts (Rayer 1987, Thompson 1989, Thornes and Shao 1991a). This paper presents the results of two possible methods designed to improve its operational performance. Both methods could be used with other similar models.

In an attempt to reduce the considerable time taken to input data into MORIPM each winter day, for over 100 forecast sites around the United Kingdom, the output of the Meteorological Office mesoscale model has already been tailored to provide input into the model on an experimental basis (Buchanan 1990, Farmer and Tonkinson 1989). As the mesoscale model grid-points are not exactly coincidental with specific forecast sites, this paper examines the most appropriate interpolation of grid-point values to the forecast sites.

Another important task in improving the operational efficiency of road ice prediction models is to reduce the systematic errors of the ice prediction model. MORIPM has a negative bias of about 1 °C (Thornes and Shao 1991a). However, a small negative bias (of say 0.25°C) is preferred to no bias at all in order to reduce the risk of skidding accidents (Thornes 1989). The negative bias is caused by both model failure in simulating physical processes and the necessary use of 'blank' parameters that the model has to adopt, such as the thermal properties and construction of the road, topography, shadow angles and traffic. The use of an averaging templet is suggested which takes the mean hourly error over the previous 7 days and applies it as a correction factor to the hourly forecast curve for the next 24 hours.

2. A combination scheme for the mesoscale output

A convenient formulation that expresses the value of a variable at a specific field site in terms of a linear combination of grid values is an equation such as

$$V^{f} = \sum_{i=1}^{n} W_i V_i^{g} \qquad (1)$$

where V^{f} is the interpolated or analysed value of the variable V at the field site f, W_i represents the weight applicable at the grid-point i, V^{g} is the mesoscale output

of variable V at the grid-point i, and n is the number of neighbouring grid-points which are assumed to be of influence to the site.

The weights in equation (1) are obtainable from distance–neighbour functions called 'weight parameters'. It is the derivation of these parameters and how they enter the weight calculation procedure that is of concern. Here, the weight parameter for the grid-point i in the field site f is given by the formula

$$W_i = w_i / \sum_{i=1}^{n} w_i \qquad (2)$$

where

$$w_i = (R^2 - D_{fi}^2)/(R^2 + D_{fi}^2) \qquad (3)$$

$$D_{fi}^2 = (x_f - x_i)^2 + (y_f - y_i)^2. \qquad (4)$$

Here, D_{fi} is the distance between site f and grid-point i, and R is the 'radius of influence' beyond which grid-points cease to be considered. For the first stage of the investigation, R is assumed to be the length of a diagonal line in the four-grid-point network which is shown in Fig. 1.

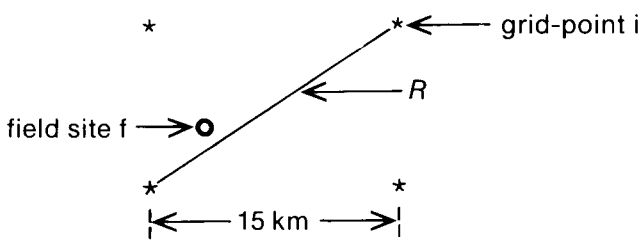

Figure 1. The four mesoscale grid-points and field site.

In order to take altitude into account, the grid-point values of each variable such as air temperature and wind speed need to be extrapolated to an equivalent value at the same altitude as that of the field site, before using equations (1) to (4). Here air temperature is extrapolated according to an average lapse rate, i.e. −0.65 °C/100 m. Wind speed is extrapolated by an equivalent power law exponent

$$U_2 = U_1(z_2/z_1)^a \qquad (5)$$

where 'a' is given analytically by (for simplicity, under neutral stability, e.g. high winds)

$$a = \frac{1}{\ln(z_g/z_0)} \qquad (6)$$

and

$$z_g = (z_1 z_2)^{1/2}. \qquad (7)$$

Here z_0 is the surface roughness length (m), which is always assumed to be 0.03 m, as for low grass, steppe.

In order to find the best combination of the considered mesoscale outputs, they were combined in the following three schemes:

(a) Meso-4a method: neither air temperature or wind speed is extrapolated,

(b) Meso-4b method: only air temperature is extrapolated, and

(c) Meso-4c method: both air temperature and wind speed are extrapolated.

The whole procedure of the objective analysis is shown in Fig. 2.

3. Application of the combination scheme

The scheme was applied to MORIPM for 11 sites in England and Scotland. The sites chosen for the

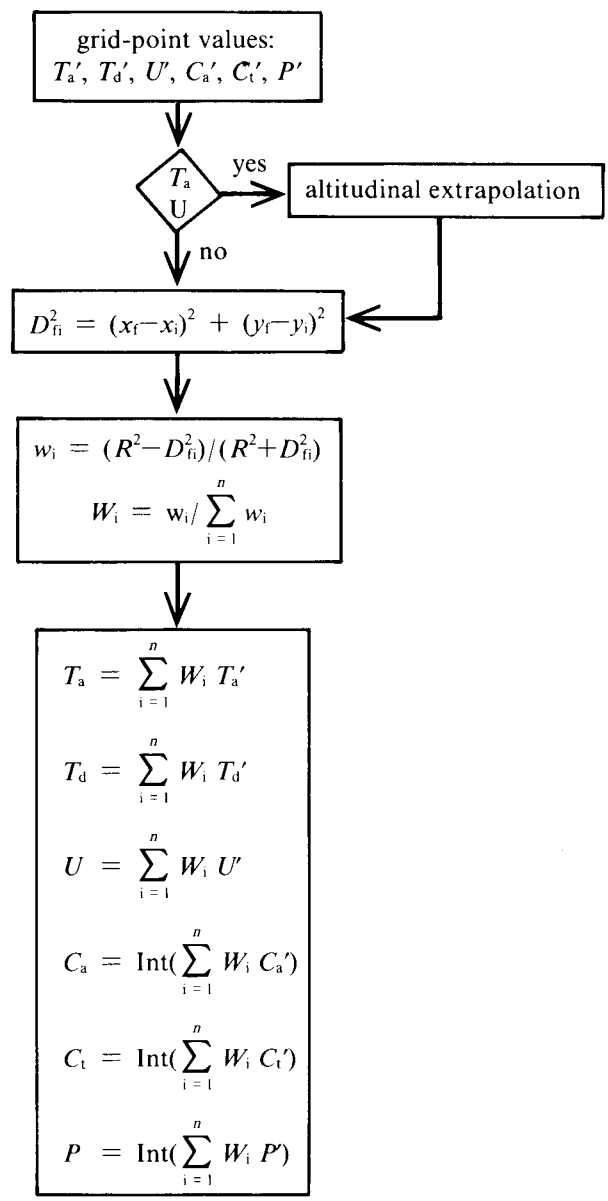
grid-point values:
T_a', T_d', U', C_a', C_t', P'
T_a U
yes
altitudinal extrapolation
no
$D_{fi}^2 = (x_f - x_i)^2 + (y_f - y_i)^2$
$w_i = (R^2 - D_{fi}^2)/(R^2 + D_{fi}^2)$
$W_i = w_i / \sum_{i=1}^{n} w_i$
$T_a = \sum_{i=1}^{n} W_i T_a'$
$T_d = \sum_{i=1}^{n} W_i T_d'$
$U = \sum_{i=1}^{n} W_i U'$
$C_a = \mathrm{Int}(\sum_{i=1}^{n} W_i C_a')$
$C_t = \mathrm{Int}(\sum_{i=1}^{n} W_i C_t')$
$P = \mathrm{Int}(\sum_{i=1}^{n} W_i P')$

Figure 2. Flow chart of the procedure of the objective analysis. T_a=air temperature, T_d=Dew-point, U=wind speed, C_a=cloud amount, C_t=cloud type and P=rainfall.

application and their relevant four mesoscale grid-points are listed in Table I with coordinates and height. The required input data for MORIPM includes air temperature, dew-point, wind speed, total and low-cloud amount, dominant cloud type, and rainfall. They are all required at 3-hourly intervals. The input data used in this study covers the period from 2 to 24 January 1991. For comparison actual roadside measurements at the sites were used, and cloud data was derived from the nearest airport or Weather Centre for each site.

In order to verify the method introduced below, MORIPM was run first against the actual roadside input (called perfect prognosis) and then against the mesoscale inputs. The results are given in Table II. As root-mean-square (r.m.s.) error can be regarded as a measure of total prediction error, the mean r.m.s. errors averaged over 11 sites are listed at the bottom of the table. It is seen from the table that for perfect prognosis (with actual roadside input) a cold bias exists at most of these sites.

Comparing the model forecasts with a single mesoscale grid-point (column '2') with those with four-grid-points (columns '3', '4' and '5'), it is clear that the combination method gives better results in overall and minimum-temperature prediction for most of the sites. The method combining four grid-point values without any extrapolation (column '3') is generally superior to the single grid method (column '2', comparing SD of overall errors 8 out of 11 sites are better) and other combination methods with wind speed and/or air temperature extrapolations. This is probably due to the fact that the assumption of a general or neutral extrapolation profile of air temperature and wind speed is not suitable.

4. Templet for site specific correction

Results (Thornes and Shao 1991a, Farmer and Tonkinson 1989) have shown that the Meteorological Office road ice prediction model has an obvious cold bias, which may be caused by both its simulation of

Table I. Coordinates (NGR) and height (m) of specific sites and the nearby mesoscale grid-points

Site code/name			Site	Grid a	Grid b	Grid c	Grid d
BO001	West Linton	X	3149	3100	3250	3100*	3250
		Y	6520	6550	6400	6400	6550
		height	200	361	361	270	317
BR006	Windsor Park	X	4945	4900	5050	4900*	5050
		Y	1724	1750	1600	1600	1750
		height	88	53	42	73	38
CH007	Siddington	X	3844	3700	3850*	3700	3850
		Y	3709	3850	3700	3700	3850
		height	30	46	94	34	37
GR003	Tyrebagger	X	3840	3700*	3850	3700	3850
		Y	8120	8200	8050	8050	8200
		height	36	151	102	150	108
HW010	Chapman's Hill	X	3964	3850	4000	3850	4000*
		Y	2775	2800	2650	2650	2800
		height	200	79	106	39	184
IN002	Slochd Summit	X	2626	2500	2650	2500*	2650
		Y	8262	8350	8200	8200	8350
		height	380	—	—	—	—
KB003	Grange Moor	X	4224	4150	4300	4150*	4300
		Y	4155	4300	4150	4150	4300
		height	220	235	168	404	80
RO013	Stubbin Road	X	4420	4300	4450	4300	4450*
		Y	3977	4000	3850	3850	4000
		height	60	168	48	211	51
SF001	Barton Mills	X	5726	5650*	5800	5650	5800
		Y	2738	2800	2650	2650	2800
		height	10	34	17	61	39
WN002	Ray Hall	X	4022	4000	4150	4000	4150*
		Y	2938	2950	2800	2800	2950
		height	123	162	128	184	98
XM005	Thurcroft	X	4478	4450	4600*	4450	4600
		Y	3885	4000	3850	3850	4000
		height	100	51	63	48	47

* The grid was chosen by the Meteorological Office as a representative site for the road site and is used in a single grid-point data set.

Table II. Bias and standard deviation of model forecasts with roadside and mesoscale inputs (January 1991)*

Site code		Overall errors 1	2	3	4	5	Errors in minimum temperature 1	2	3	4	5
BO001	bias:	−0.91	0.33	−0.44	−0.08	−0.25	−1.24	0.59	−0.265	0.12	−0.10
	SD:	1.28	1.33	1.30	1.35	1.35	1.46	1.42	1.35	1.41	1.41
BR006	bias:	−0.70	−0.25	−0.40	−0.52	−0.50	−0.64	0.11	−0.15	−0.26	−0.24
	SD:	0.97	2.05	2.05	2.07	2.07	1.08	2.26	2.26	2.26	2.28
CH007	bias:	−0.59	0.22	0.07	0.17	0.02	−0.57	0.57	0.41	0.50	0.30
	SD:	0.85	1.83	1.76	1.79	1.75	0.86	2.14	1.98	1.97	1.91
GR003	bias:	−1.12	−0.85	−0.67	−0.40	−0.69	−1.14	−0.90	−0.81	−0.53	−0.86
	SD:	1.18	1.64	1.61	1.54	1.65	1.25	1.35	1.59	1.61	1.62
HW010	bias:	−1.33	−1.06	−1.06	−1.32	−1.29	−1.47	−0.85	−0.97	−1.25	−1.21
	SD:	1.39	2.65	2.63	2.61	2.63	0.89	3.11	3.03	3.00	3.02
IN002	bias:	0.30	1.80	0.88	—	—	0.82	2.34	1.49	—	—
	SD:	1.20	1.59	1.39	—	—	0.63	1.70	1.54	—	—
KB003	bias:	0.50	0.71	0.57	0.75	0.64	0.80	1.33	1.07	1.27	1.14
	SD:	0.84	1.59	1.60	1.61	1.62	0.87	1.76	1.85	1.83	1.85
RO013	bias:	−0.93	−0.72	−0.76	−0.79	−0.81	−1.22	−1.06	−0.87	−1.10	−1.04
	SD:	1.07	1.95	1.88	1.95	1.95	1.11	2.24	2.19	2.27	2.30
SF001	bias:	−0.34	−0.94	−0.99	−0.89	−1.00	0.27	−0.36	−0.40	−0.28	−0.44
	SD:	0.83	1.71	1.73	1.73	1.71	0.81	2.06	2.04	2.03	1.97
WN002	bias:	−1.36	−1.28	−1.44	−1.36	−1.45	−1.56	−1.46	−1.51	−1.43	−1.55
	SD:	1.68	2.35	2.32	2.31	2.33	0.92	2.74	2.86	2.85	2.87
XM005	bias:	−0.40	−0.84	−0.80	−0.96	−0.94	−0.56	−1.00	−0.88	−1.07	−1.06
	SD:	0.78	2.23	2.00	2.00	2.00	0.77	2.63	2.32	2.33	2.33
Mean	r.m.s.	1.31	2.09	1.99	2.04	2.05	1.37	2.40	2.28	2.32	2.33

* 1 — forecasts with roadside input;
2 — single mesoscale grid-point;
3 — four mesoscale grid-points without any extrapolation;
4 — four mesoscale grid-points with air temperature extrapolated;
5 — four mesoscale grid-points with both air temperature and wind speed extrapolated;
SD — standard deviation (°C);
r.m.s. — root-mean-square error (°C).

physical processes, and by the unpredictable influences of topography, altitude, traffic and many other unknown factors, such as the thermal properties of road construction. To eliminate the cold bias or any other systematic error, the use of a templet is introduced here. The mean error (E) and variance (σ^2) of the model prediction are estimated by:

$$E = \frac{1}{n}\sum_i(\hat{X}_i - X_i) = \frac{1}{n}\sum_i(\mathrm{d}x_i) \qquad (8)$$

$$\sigma^2 = \frac{1}{n}\sum_i[(\hat{X}_i - X_i) - E]^2 = \frac{1}{n}\sum_i(\mathrm{d}x_i - E)^2 \qquad (9)$$

where $\hat{X}_i$ is initial hourly prediction, X_i observation (reality), and $\mathrm{d}x_i$ an unknown error of prediction. In order to reduce prediction error, an hourly averaging templet is applied to each hourly predicted value, i.e.

$$\hat{X}_i' = \hat{X} - \mathrm{d}x_i' \qquad i=1, 2, ..., 24. \qquad (10)$$

Here, $\hat{X}_i'$ is the corrected prediction, $\mathrm{d}x_i'$ the mean hourly error of prediction of previous days. The mean error (E') and variance ($\sigma^{2\prime}$) of the prediction with a templet are

$$E' = \frac{1}{n}\sum_i(\hat{X}_i' - X_i) = \frac{1}{n}\sum_i(\mathrm{d}x_i - \mathrm{d}x_i') \qquad (11)$$

and

$$\sigma^{2\prime} = \frac{1}{n}\sum_i[(\hat{X}_i' - X_i) - \frac{1}{n}\sum_i(\hat{X}_i' - X_i)]^2$$

$$= \sigma^2 - \frac{2}{n}\sum_i(\mathrm{d}x_i - \overline{\mathrm{d}x})(\mathrm{d}x_i' - \overline{\mathrm{d}x'})$$

$$+ \frac{1}{n}\sum(\mathrm{d}x_i' - \overline{\mathrm{d}x'})^2 \qquad (12)$$

where an overbar stands for averaging.

The estimation of hourly prediction error ($\mathrm{d}x_i'$) is expected to approximate to the real error ($\mathrm{d}x_i'$) with a small deviation (e_i), i.e.

$$dx_i = dx_i' + e_i \quad (13)$$

and

$$\overline{dx} = \overline{dx'} + \bar{e}. \quad (14)$$

Substituting equations (13) and (14) into equations (11) and (12), E' and $\sigma^{2\prime}$ are rewritten as

$$E' = \frac{1}{n}\sum_i e_i \quad (15)$$

and

$$\sigma^{2\prime} = \sigma^2 - \frac{2}{n}\sum_i (dx_i' + e_i - \overline{dx'} - \bar{e})(dx_i' - \overline{dx'}) + \frac{1}{n}\sum_i (dx_i' - \overline{dx'})^2$$

$$= \sigma^2 - \frac{1}{n}\sum_i (dx_i' - \overline{dx'})^2 - \frac{2}{n}\sum_i (e_i - \bar{e})(dx_i' - \overline{dx'}). \quad (16)$$

It is seen from equation (15) that the mean error of the corrected prediction is approximately zero as e_i is expected to be the difference between dx_i and dx_i'. In equation (16), if the third term is neglected (i.e. estimated hourly error approximates to real error), the variance or standard deviation (SD $= + \sqrt{\sigma^2}$) of corrected prediction will be smaller than that of initial prediction. Therefore, it is reasonably expected that with a proper estimation of hourly initial prediction error, the accuracy of model prediction can be improved by subtracting the estimates from the initial predictions. After the correction, the bias is expected to be around zero and the standard deviation to be reduced. The simplest way to get an estimation of hourly prediction error is to average the error of previous days by comparing observations and predictions. This method is called an 'averaging templet'.

In getting the above results, an assumption has been implicitly introduced, i.e. initial prediction error is systematic and easily estimated. Thus the question arises: how can the estimation of initial prediction error be optimized before using the templet method?

A meteorological variable, as well as the road surface temperature (RST) or the model prediction error in RST, is expected to consist of periodic components. To draw as much information as possible from the difference between model predictions and actual observations for estimating the initial model prediction error, the hidden periodicity in the series of the RST difference should be revealed so that the averaging time for a templet is able to cover an integral period of the variation of the series. This has been done by using spectral analysis on road surface temperature data for the winter of 1988/89 at the Chapman's Hill road weather site on the M5 (Thornes and Shao 1991b). The results showed that the series of model prediction has dominant periodicity around 3, 5 and 7 days. An estimation of initial prediction error over one of these periods is representative of the optima.

5. Validation of the templet

The templet method was first used for winter 1990/91 for the 11 sites given in Table I, with actual roadside input to validate the effectiveness of the method. The results are given in Table III. As a demonstration, the hourly biases and standard deviations of sites GR003 and WN002 without and with a templet are shown in Figs 3 and 4. From the figures, it is seen that the cold bias has been removed by the templet. The frequency distribution of the difference between actual and predicted minimum temperatures for the model is shown in Figs 5 and 6. About 40% of the minimum road temperature forecasts with the templet are of an accuracy ±0.5 °C, and 57.3% (Tyrebagger) and 74.2% (Ray Hall) of the forecasts are within ±1 °C. The improvement in minimum forecast using a templet is 10–20%.

In order to see its generality and usefulness in real-time model runs, the method was then applied for ten sites using realistic or forecast inputs. Table III summarizes the results.

From Table III and Figs 3–6, an improvement in the model prediction by using an averaging templet is obvious. The most notable improvement is in the bias which is reduced very significantly. No matter how big the bias is, the templet reduces it close to zero. On the other hand, there is very little change in the standard deviation. Comparing the results in both bias and standard deviation, the corrected predictions are much better than those without a templet in both overall hourly predictions and minimum temperature prediction for almost all of the sites. For the real-time application of the method, Table IV shows that:

(a) the method improved the model real-time forecasts for most sites by significantly removing bias, especially for the overall forecasts;
(b) there is no large difference between using a 5-day or 7-day templet;
(c) for some sites (Barton Mills (SF001) and Grange Moor (KB003)), the method deteriorates the forecasts where the initial model forecasts were of small bias.

The above results demonstrate that an averaging templet is a useful tool to delete systematic errors in model predictions. It is clear that the method is potentially useful to increase the accuracy of real-time forecasts, although the results may not be so good as with perfect prognosis. It must also be remembered that for real-time use a negative bias of about 0.25 °C is desirable, as discussed in Thornes (1989). The templet can easily be adjusted to achieve this.

Table III. Bias and standard deviation of model forecasts with an averaging templet* (roadside input, November–February 1990/91)

Site code		Overall errors				T_{min} errors			
		A	B	C	D	A	B	C	D
BO001	bias:	−0.83	−0.01	0.01	0.01	−1.15	−0.20	−0.13	−0.11
	SD:	1.22	1.21	1.21	1.18	1.19	1.19	1.24	1.23
BR006	bias:	−0.56	0.00	0.01	0.03	−0.34	0.05	0.21	0.27
	SD:	0.98	1.04	1.00	0.98	0.87	1.06	1.00	0.94
CH007	bias:	−0.31	−0.01	−0.02	−0.01	−0.17	0.11	0.16	0.19
	SD:	0.98	1.02	1.00	0.97	0.93	0.94	0.95	0.95
GR003	bias:	−0.98	−0.02	−0.02	0.04	−0.97	−0.12	0.16	0.05
	SD:	1.07	1.14	1.00	1.12	1.14	1.20	0.95	1.20
HW010	bias:	−0.77	−0.03	0.00	0.01	−0.78	−0.59	−0.14	−0.03
	SD:	1.20	1.33	1.19	1.16	0.96	1.76	1.08	0.98
IN002	bias:	0.05	−0.01	0.01	0.03	0.32	0.02	0.17	0.22
	SD:	1.14	1.32	1.22	1.19	0.97	1.14	1.04	0.97
KB003	bias:	0.26	−0.02	−0.02	−0.01	0.65	0.13	0.23	0.29
	SD:	0.95	1.05	1.00	1.00	0.98	1.08	1.06	1.08
RO013	bias:	−0.76	−0.01	0.00	0.01	−0.93	−0.07	−0.01	0.04
	SD:	0.88	0.85	0.82	0.81	0.78	0.85	0.82	0.83
SF001	bias:	−0.37	−0.01	0.00	0.01	0.01	0.11	0.18	0.22
	SD:	0.88	0.92	0.88	0.88	0.83	0.89	0.88	0.87
WN002	bias:	−0.87	−0.04	−0.02	0.00	−0.90	−0.20	−0.06	0.01
	SD:	1.11	1.17	1.11	1.09	1.01	1.19	1.07	1.04
XM005	bias:	−0.29	0.00	−0.01	0.00	−0.21	−0.01	0.04	0.06
	SD:	0.83	0.86	0.82	0.81	0.72	0.6	0.73	0.73
Mean	r.m.s.	1.19	1.08	1.02	1.02	1.15	1.10	0.98	0.98

* A — without templet
B — with a 3-day templet
C — with a 5-day templet
D — with a 7-day templet.

6. Conclusion

From the above results the following conclusions can be drawn:

(1) The output of the Meteorological Office mesoscale model can be linearly combined using four-grid-point values to give a better input data set for a specific site for the Meteorological Office road ice prediction model. For the 11 sites chosen for the investigation, eight of them showed improvements in the predictions of overall temperatures.

(2) The averaging templet method is a useful tool to delete systematic prediction error and increase prediction accuracy for the Meteorological Office road ice prediction model in overall and minimum temperature predictions.

As for an optimal averaging period for the templet method, 3, 5 and 7 days are suitable candidates. Too short a period may be unable to cover a necessary range of road-surface temperature variations in order to smooth the fluctuation of prediction error. A longer period (more than 7 days) contains too much 'old' information that has lost its usefulness, especially for minimum prediction. To take into account the weekly cycle of traffic, a 7-days averaging period is preferable.

For real-time use the forecaster should be able to deselect the templet option if the weather conditions are set to change significantly from the previous few days weather.

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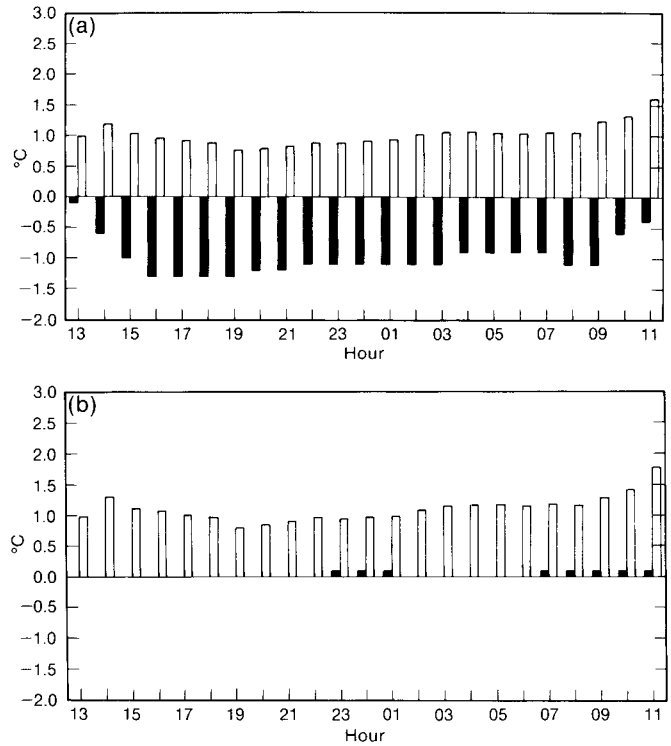

Figure 3. Mean hourly bias (shaded) and standard deviation (unshaded) of model forecasts (a) without a templet and (b) with a 7-day templet (roadside input for Tyrebagger, winter 1990/91)

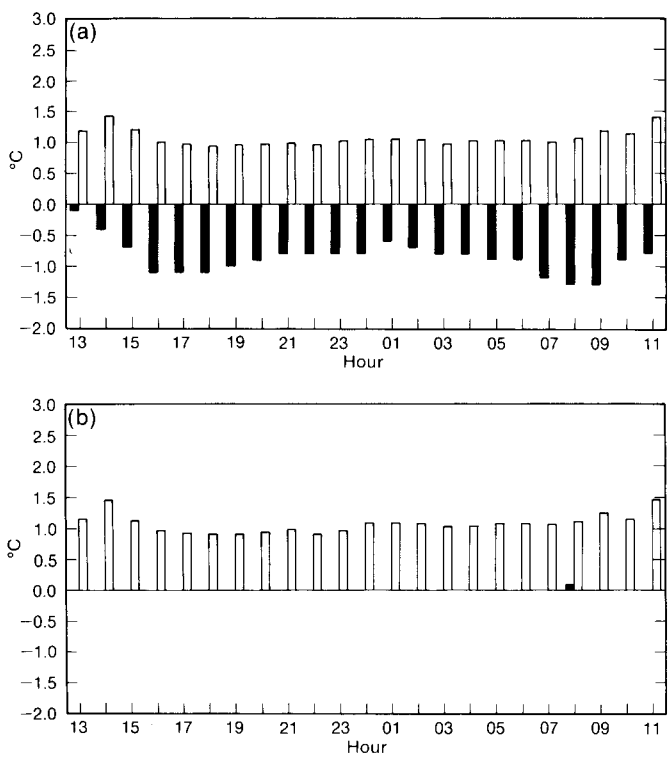

Figure 4. Mean hourly bias (shaded) and standard deviation (unshaded) of model forecasts (a) without a templet and (b) with a 7-day templet (roadside input for Ray Hall, winter 1990/91).

Table IV. Comparison of Meteorological Office model forecasts with and without a templet (realistic inputs, November 1989)

Site code		No templet bias	No templet SD	5-day templet bias	5-day templet SD	7-day templet bias	7-day templet SD
XM005	overall	−0.55	1.119	0.02	1.150	0.05	1.178
	min. temp.	−0.36	1.197	0.23	1.372	0.20	1.378
GR003	overall	−1.47	1.730	−0.10	1.866	−0.21	1.955
	min. temp.	−1.79	1.652	−0.37	2.223	−0.24	2.456
IN002	overall	−0.83	1.457	−0.08	1.276	−0.29	1.266
	min. temp.	−0.50	1.441	0.20	1.341	−0.09	1.306
SF001	overall	−0.69	1.737	0.18	1.772	0.23	1.878
	min. temp.	−0.36	1.260	0.41	1.330	0.52	1.439
BR006	overall	−1.24	1.521	−0.18	1.616	−0.22	1.519
	min. temp.	−1.15	1.409	−0.24	1.854	−0.22	1.461
CH007	overall	0.67	2.075	0.13	2.471	0.33	2.444
	min. temp.	1.39	1.927	0.92	2.477	1.20	2.343
KB003	overall	0.02	1.362	0.03	1.641	0.13	1.456
	min. temp.	0.15	1.445	−0.07	2.013	0.06	1.733
RO013	overall	−0.76	1.973	−0.20	1.787	−0.31	1.615
	min. temp.	−1.37	1.990	−0.15	2.146	−0.30	2.059
WN002	overall	−0.77	2.085	−0.06	2.364	−0.16	2.259
	min. temp.	−0.61	1.729	−0.03	2.107	0.05	2.060
BO001	overall	−0.88	2.171	−0.21	2.274	−0.21	2.265
	min. temp.	−1.54	2.385	−0.49	2.554	−0.32	2.425
Mean r.m.s.	overall	1.93		1.83		1.80	
	minimum	1.93		1.98		1.91	

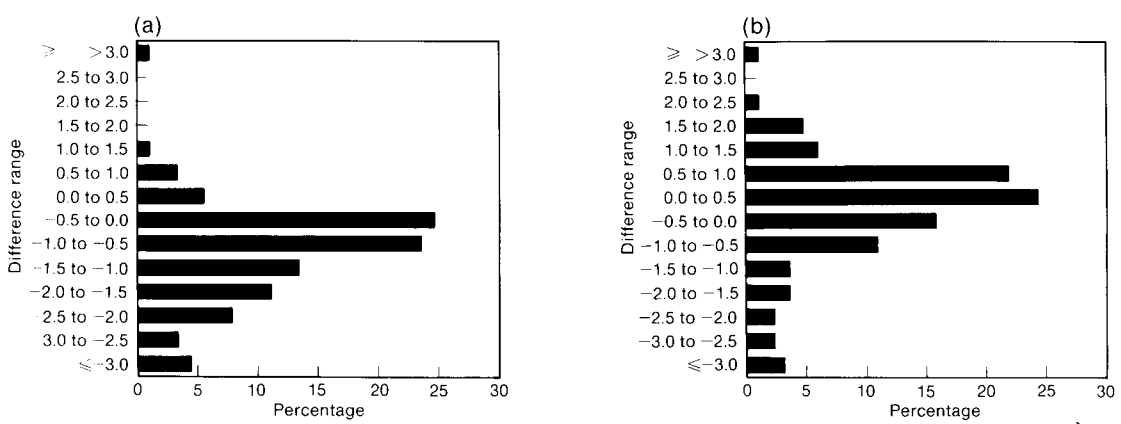

Figure 5. Frequency distribution of the difference of minimum temperature (a) without a templet and (b) with a 7-day templet (roadside input for Tyrebagger, winter 1990/91).

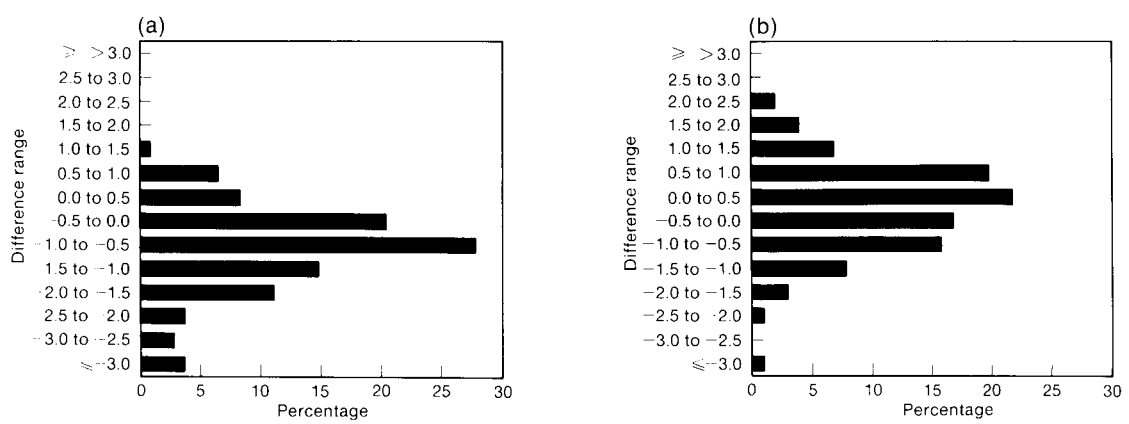

Figure 6. Frequency distribution of the difference of minimum temperature (a) without a templet and (b) with a 7-day templet (roadside input for Ray Hall, winter 1990/91).

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United Kingdom synoptic meteorological observing — past, present and future

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Summary

The history and current state of the UK synoptic network is reviewed in the light of current developments in the automation of observing.

1. Introduction

This paper describes the UK synoptic observing network and its current configuration. Developments in the network are discussed and also the ways in which the needs of the user will be met. These needs relate to the WMO requirements for data for exchange over the Global Telecommunication System (GTS), to numerical weather prediction models of increasing resolution, to or national forecasters and to the local forecasting or nowcasting requirement, especially for aviation. A look is taken at the UK observing scene in some 20 years' time.

2. Observing network

The need for a network of observations all made at the same time and in the same way had been recognized by Robert Hooke in 1663. In 1838 John Ruskin rationalized upon the need for an observing network, noting that '... the individuals should think, observe and act simultaneously, though separated from each other by each other by distance on the greatness of which depended the utility of the observations'.

The potential value of such a network was demonstrated when Napoleon III asked his astronomer royal, Le Verrier, to study a storm in the Black Sea (14 November 1854) during the Crimean War, when some 40 allied ships were lost. Le Verrier was able to show that the storm was a coherent circulation of winds, around a centre of low pressure, which had moved as an entity in a gently curving track. From this study it was apparent that, on the basis of extrapolation alone, weather prediction over a few hours at least was possible in principle. Observing networks for operational purposes began to be developed from the mid to late 1850s when the first meteorological services were created and when, importantly, the electric telegraph was developing as a means for transmitting data quickly. The Great Exhibition of 1851 saw the first 'near real-time' maps of actual weather derived from these messages. The maps sold for one penny a piece (then the price of a postage stamp).

3. The UK surface synoptic network

Admiral FitzRoy started the early operational observing networks run by the Meteorological Office, but these were limited in that the observers had to have access to the telegraph. In 1880 there were some 36 synoptic stations, many of which were at lighthouses or coastguard stations. In 1920 the Office came under the aegis of the newly formed Air Ministry and a major component of its work was directed to serving aviation in general and to the Royal Air Force in particular. Observations became available from airfields.

In the early 1920s there were around 45 to 50 synoptic observing stations, 20 or so of these were official stations — observatories or distributive stations. The latter name was coined because their data were collected on a distributed scheme through collecting centres. The remaining 25 or so stations continued to be known as telegraphic stations for obvious reasons, and they corresponded to the current auxiliary synoptic stations in that they were manned by coastguards, lighthouse keepers, etc.

Just prior to the Second World War the annual report of 1939 quoted the total number of stations at 51. During the war the number of airfields rapidly increased and the reporting network reached its densest ever at 550, mostly in the eastern half of Britain with the many RAF and US Air Force bases. Within 18 months of the war's end the number of observing sites had halved and subsequently the number of officially manned stations decreased to around 80; the number of auxiliary stations increased to around 180 in the 1970s, but has now decreased to about 100.

The manned official observing sites are still mostly at airfields, while the auxiliary sites are chosen to fill gaps in the network and to meet specific operational requirements. Clearly, throughout its history the Office has had little real control over the shape and size of its observational base. In the ideal situation the network observing sites would be planned in such a way as to represent those weather features sufficiently long-lived to be worth predicting, and at the same time represent

adequately the different climatological areas of the United Kingdom.

Because the ideal is far removed from the practical, the Meteorological Office Working Group on United Kingdom Observing Networks (WGUKON) was created to consider the needs for observations. It advises upon network design and has developed policies for all networks, synoptic, offshore, climatological, rainfall stations and radar (but radiation and sunshine have yet to be completed). These enable the actuality to be compared to an ideal and point to actions necessary to bring each network up to an acceptable standard. A policy for synoptic networks is contained in a paper known as UKON 1. The basics of this are as follows:

(a) There will be a key synoptic station network, comprising some 30 stations reporting hourly throughout the 24 hours. These stations will be fully equipped and manned by professional meteorologists for the observing function, so that every observation complies with the full WMO requirements for a SYNOP from a principal land station. These stations are about 90 km apart on average, although the network is not very even and in some areas the spacing approaches 200 km. The WMO recommendation is that the space between stations on a regional basic synoptic network should not exceed 250 km.

(b) There will be a number of secondary stations associated with each key station depending upon the area in which the latter is considered to lie. These stations will represent coastal areas facing representative directions, inland areas, both high and low ground and areas of particular interest, e.g. the Thames Valley, the Upper Clyde Valley, major conurbations and recreational areas. Secondary stations may be fully manned to WMO PLS (Principal Land Stations) standard and they may be fully manned, automatic or part-manned/part-automatic. The minimum requirement for secondary stations is that they should report pressure, winds, temperatures and precipitation, not less frequently than every 3 hours. The UKON 1 policy currently calls for 85 secondary stations, with at least one being fully manned in each key station area.

(c) There will be an unspecified number of Supplementary Observing Stations, these stations will report as necessary to meet the needs of local forecasting and other operational requirements for weather observations. Some conform to the full WMO PLS specifications, others fall far short.

4. Implementation of UKON 1 policy

4.1 Key stations

The UKON key stations, secondary stations and associated areas are shown in Fig. 1: six of the key stations are located at radiosonde stations, a further three are at locations where the main function is surface weather observing, and the remainder are at aviation stations where there is a current need for full-time professional observers. Such a need does of course depend upon the operational requirement, and where a local user need ceases then the Meteorological Office may keep staff on site, upgrade another station to key status or, sometimes, open an office purely for synoptic observing function. For example, Dunkeswell opened when there was no longer a need for Office staff at Exeter Airport. However, such offices are regarded as undesirable in terms of the use of staff time, and whenever possible the policy is to try to collocate surface synoptic observing with other functions, such as upper-air observing, observatory work or aviation services. As well as being chosen for their meteorological attributes, key stations should also have a reasonable likelihood of a long operational life — major airports and important RAF bases are good examples.

4.2 Secondary stations

Airfield closures, availability of suitable sites, and the pressure to reduce costs have made it impossible to sustain a Meteorological Office-manned secondary station network to the levels defined in the UKON policy paper. Application of the policy has led to the selective recruitment of auxiliary observers and to the deployment of some fully automatic stations, typically the Synoptic Automatic Weather Stations (SAWS) in order to fill gaps in the network.

4.3 Supplementary stations

At other meteorological stations where there is a flying commitment, observers have to be present during flying hours. Such stations may be closed at weekends and nights so the density of stations reporting depends upon the time of day and the day of week. Requirements for data to meet specific user requirements, other than on operational airfields, may be met by the recruitment of auxiliary observers, by automatic stations, or by Meteorological Office staff on an opportunity basis. Fig. 2 shows the maximum hourly coverage of observations when all are reporting, while Fig. 3 shows the minimum observational coverage. Both of these figures are valid for spring of 1992.

5. Implementation of automated observing systems

The initial concept for automated observing in the United Kingdom was for a system that would operate at remote sites, generating limited SYNOPs consisting only of temperature, dew-point, pressure, wind and 6-hourly rainfall totals. Subsequently these SAWS systems were enhanced to measure hourly rainfall totals, extreme temperatures and hourly mean winds and gusts. They were also able to accept observations of radiation, visibility and cloud base, and to have extra temperature sensors fitted to give grass minimum and ground temperatures. The enhanced SAWS therefore not only provides better observational data than the original, but

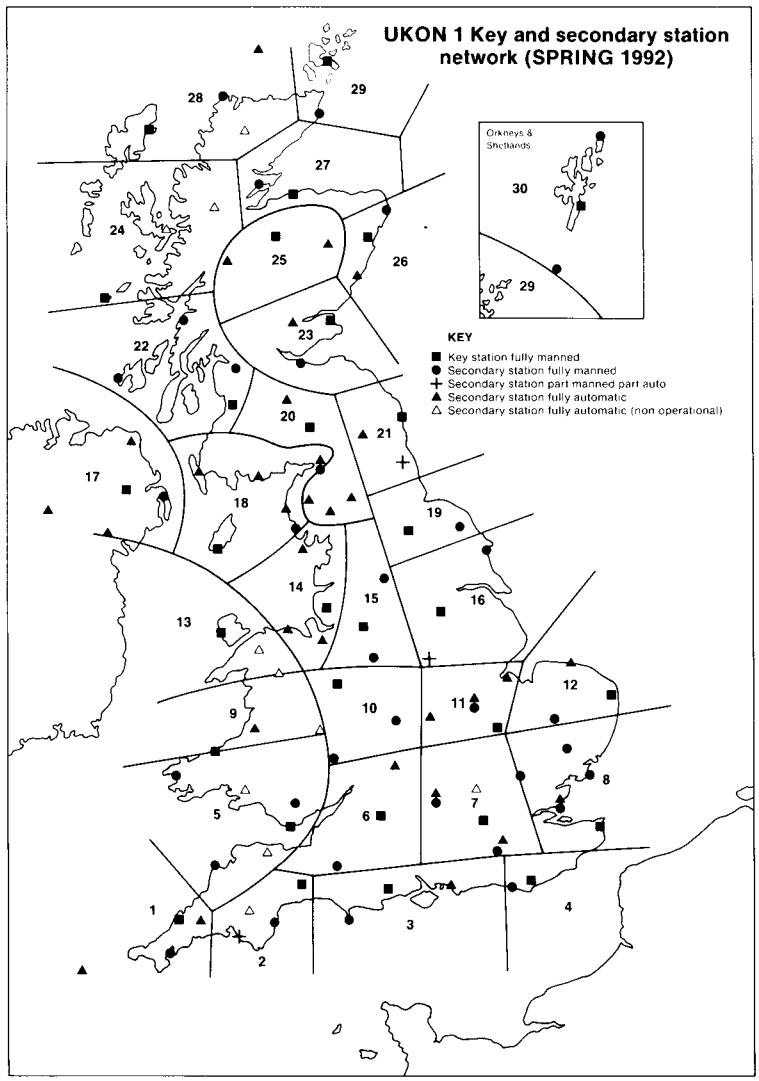
UKON 1 Key and secondary station network (SPRING 1992)
Orkneys & Shetlands
KEY
Key station fully manned
Secondary station fully manned
Secondary station part manned part auto
Secondary station fully automatic
Secondary station fully automatic (non operational)

Figure 1. The UKON 1 key and secondary station network as at the spring of 1992. Note that several areas, e.g. 9, 13, 21 and 25 do not meet UKON 1 policy in that there are no manned secondary stations.

is also able to act as a principal automatic climatological station within the WMO definitions. Although initially limited in scope and application, the SAWS has become a successful operational system. Since their introduction the concept of applying automation to the observing functions has developed. There is still a need for systems to operate unattended like SAWS, but there is now also a requirement for systems to be able to accept additional or modified data generated by a human observer. The applications for such Semi-Automatic Meteorological Observing Systems (SAMOS) or the commercial derivative, Computer-Aided Meteorological Observing Systems (CAMOS) are seen as being fivefold:

(a) Manpower is released from the mechanical aspects of observing, such as reading, transcribing and keying of instrumental data, coding them into SYNOP or METAR format, completing the *Daily Register*, checking the data and generating the national climate message. This may allow some merging of functions, e.g. those of observer and forecaster, at quiet times.

(b) A reduced SYNOP is provided when observers are totally or partially withdrawn for reasons of economy and so maintain observing networks up to the standard for UKON 1 secondary station purposes.

(c) Night-time and weekend gaps in the observing network are filled to bring it up to the UKON 1 requirements when necessary. A station that was previously capable only of meeting supplementary station needs, because of its operating hours, can fairly cheaply be brought up to the frequency of observing that is required of a secondary station.

(d) With minimum interference to their ATC functions, Air Traffic Control staff are enabled to produce METARs and, as a by-product, to generate the SYNOP.

(e) Uniform standards of observing and coding are maintained at all stations, thus saving some time and costs of training observers.

Even when envisaging the most advanced automation of observing there are still some parameters which

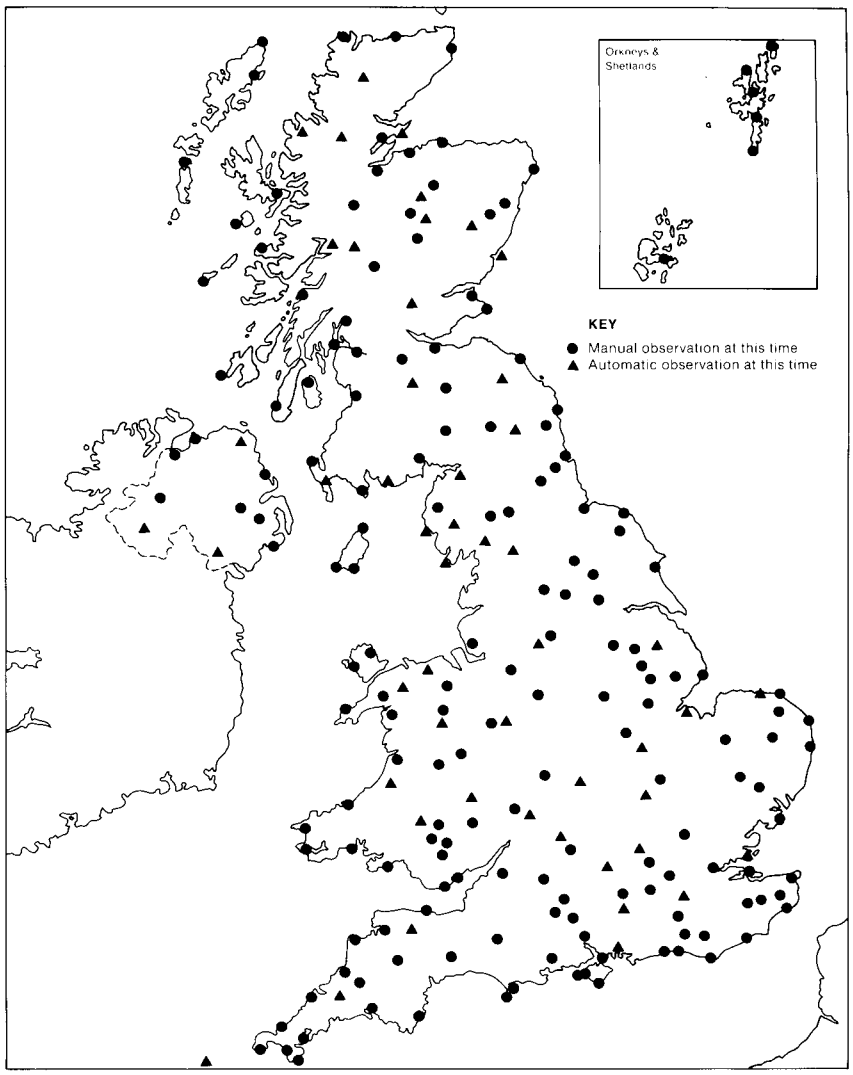

Figure 2. The maximum hourly cover of observations (at 0900 UTC on weekdays) as at the spring of 1992.

require human input for correct observing. These are visibility, the amount, height and type of cloud, present weather and state of ground. Visiometers now available have been shown to be at least as good as a human being (at night they are somewhat better) except that they cannot cope with directional variation in visibility. Cloud-base recorders still require some degree of interpretation. While they might be programmed to give estimates of low cloud amount they are unlikely to cope with higher-level cloud amounts, they are adversely affected by some precipitation and cannot, of course, describe cloud type. Present weather devices cannot, and are unlikely ever to, cope with the '99' description of the WMO code.

From the above it is clear that an automatic system requires human assistance to produce a SYNOP to WMO standards or a METAR to ICAO requirements. It follows therefore that Meteorological Office observing policy is as follows:

(a) SYNOPs at key stations and for regional basic synoptic network purposes, i.e. for exchange over GTS, will be made with human input for the visual element and to check input from SAMOS where used.

(b) SYNOPs and METARS at Meteorological Office-manned stations where flying is taking place will be made with human input for the visual elements and to check input from SAMOS where used.

(c) At all other stations or times, SYNOPs may be made by automated systems, and if there is no human input available, will be transmitted in limited form. From remote sites such as buoys, oil rigs and platforms, such limited data may also be transmitted over GTS.

6. SAMOS programme

The programme for SAMOS includes implementation at all observing offices where there are Meteorological Office staff. The result will be that the number of stations providing hourly data throughout the 24 hours will increase, and in some areas exceed UKON 1 secondary station needs, to give a degree of redundancy in the network. SAMOS may be provided to auxiliary stations, if that is the only way that UKON 1 secondary stations can be found in some parts of the United Kingdom. Whether CAMOS is used to provide assist-

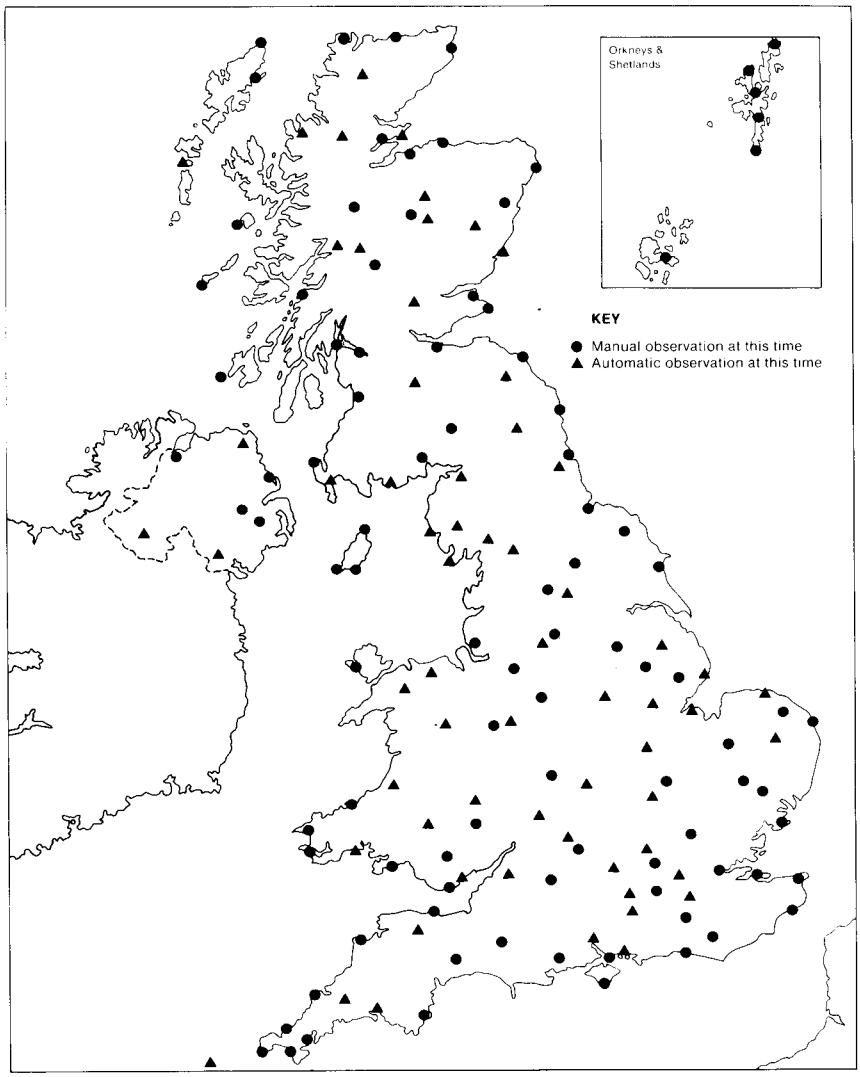

Figure 3. Minimum observational coverage (at 0300 UTC at weekends) in 1992.

ance to ATC staff at civil airports with no Meteorological Office staff is, of course, a matter for the CAA or the local airfield management. It is hoped that CAMOS will be seen as sufficiently user friendly for this, since it will improve further the UK observational network to the benefit, amongst others, of civil aviation itself.

There are still a few SAWS installations to complete. The SAMOS programme is scheduled for completion by the end of 1995/6. By then the 'maximum' network of Fig. 2 should have been augmented, with many of the SAWS and SAMOS sites being equipped with visiometers and cloud-base/low-cloud amount recorders. More importantly the 'minimum' network at Fig. 3 will also have increased in numbers to that shown in Fig. 4. Should CAMOS be implemented at civil airports where there are currently no SYNOPs provided, then the network densities will be greater than shown.

7. Message transmission and exchange

The above is a description of the current observing policies for the United Kingdom. However, it must be remembered that the SYNOP code forms and data needs, as identified by WMO, had their origins in the days before numerical weather products, and long before radar networks and satellite sensing. The use of groups of five figures, with the location of each number indicating the elements reported, dates back to 1863 when Admiral FitzRoy produced instructions for the construction of weather messages with simple present- and past-weather codes, dew-point depression, gust speeds and directions, pressure, mean winds, etc.

The form of the current WMO SYNOP report was designed to give as complete a description as possible to enable subjective and detailed analyses of small-scale weather features. Nowadays much forecasting is undertaken by computers using objective analysis techniques, enhanced by human input based on satellite cloud and radar rainfall imagery. Therefore it is pertinent to question the need for continuation of, or adherence to, the SYNOP format.

Given improvements in communication systems and data compression techniques, it is possible to consider large numbers of automatic stations producing continuous data streams of some, but not necessarily all, of the

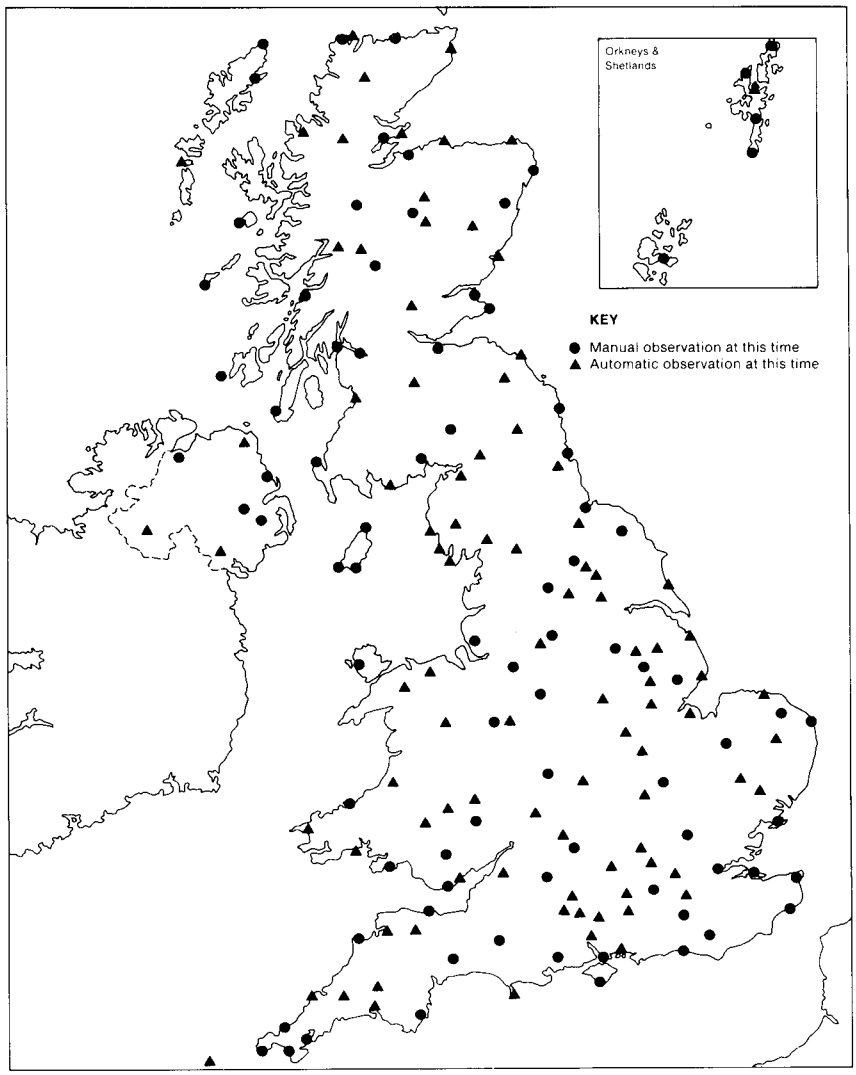

Figure 4. Minimum observational coverage at 0300 UTC by late 1996. Note the number of automated observations (cf. Fig. 3). Use of CAMOS at smaller civil airports will give even better SYNOP cover than shown.

basic data of winds, pressures, temperatures, rainfall, visibility, low-cloud amounts and heights. The climatological network is a potential source for these extra sites. At present it is largely manual, but there is an increasing need to introduce automatic stations. Fig. 5 shows the 1992 voluntary climate network. The increasing power of computers coupled with developments in objective analysis techniques is leading to the possibility of being able to use such data with near-continuous assimilation. The use of imagery in such analysis methods is also being actively explored.

For such internal, national processing of data, a coded SYNOP becomes inappropriate for either data collection or dissemination. Local area forecasters are increasingly likely to become supplied with data analyses in pictorial or digital forms, coupled with short-period predictions of the same fields. There will be no need for individual forecasters to analyse fields of pressure, wind, temperature, cloud, precipitation, etc.

8. The UK upper-air network

The radiosonde, developed during the 1930s, became an operational tool during the latter part of that decade and during the Second World War, after which there was rapid development and expansion of networks worldwide.

Early wind finding from radiosonde ascents in the United Kingdom used radio direction-finding systems with a triangle of stations around each radiosonde station, but has been replaced by radar since the mid 1940s. As part of current cost-saving measures, NAVAID wind finding has been introduced at some UK radiosonde stations using the LORAN system. From ships the NAVAID–OMEGA system is already used and is adequate, but it is unable to produce wind data of the accuracy and resolution required over the UK mainland. The main shortcoming of the radiosonde is that, for cost and logistic reasons, operational systems, typically, are only launched at 6-hour intervals. The UK

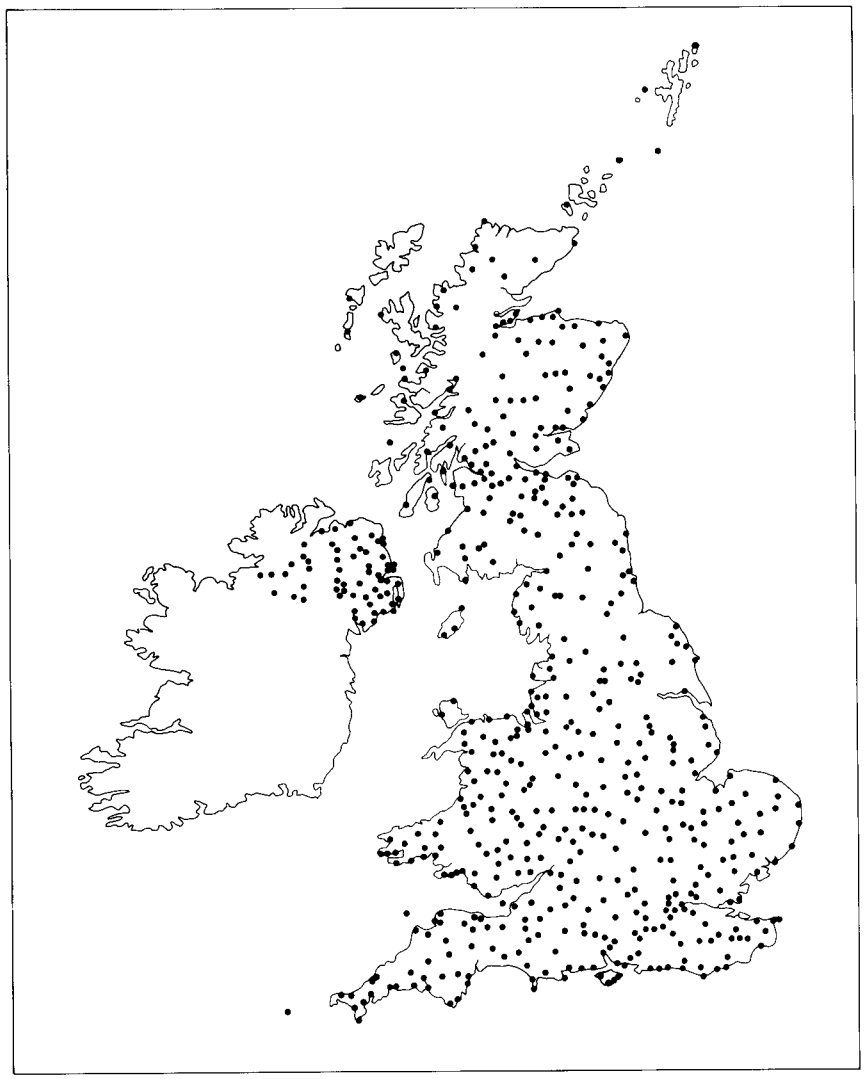

Figure 5. The voluntary climatological observing network as at early 1992. Some of these sites have the potential for a simple automatic weather station and the provision of instrumental data to enhance the synoptic networks.

radiosonde network is roughly at the WMO recommended spacing. All the stations produce wind data at 6-hour intervals, but where winds are measured by radar, the temperature and humidity ascents are made only twice a day. Because a radiosonde is needed for LORAN wind-finding these stations make temperature and humidity ascents 6-hourly. For local forecasting purposes the so-called boundary layer radiosonde is used. This is a conventional sonde system typically used up to 500 mb but not measuring winds.

In the future, satellite sounding techniques are expected to produce data of sufficient quality for large-scale temperature, humidity, pressure contour and wind analyses but are unlikely to provide detailed soundings of the kind used by forecasters. Future ground-based remote sounders may be able to produce useful detailed temperature profiles up to about 2 km, but without humidity data. At present it seems unlikely that either ground- or space-based remote sensing will completely replace the radiosonde for observing temperature and humidity profiles with great accuracy and resolution from the surface up into the stratosphere. However, early results with aircraft-to-satellite data relay (ASDAR) have shown that aircraft can produce good temperature profiles up to normal cruising altitude, but without humidity data.

Wind profilers (high-power vertical-looking Doppler radars detecting inhomogeneities in clear air) are capable of producing measurements of wind from 200 m to 14 km (working at 400 mHz) or 2 km to 20 km (at 50 mHz) with resolutions of 150 to 300 m. These systems are being studied in a number of countries, notably the USA where a network of thirty or so 40 mHz profilers is being created. Profilers operating at 400 mHz have typically a 10×10 m aerial array and may be adversely affected by precipitation. At 50 mHz a 100×100 m aerial array is needed, there is little effect from precipitation, but no wind data below 2 km. So there are

a number of problems with this technique, including some associated with frequency clearance. In principle, however, profilers offer the possibility of frequent measurements of wind over a network at least as dense as the radiosonde network. Should the data prove adequate, then profilers at around 400 mHz could prove a cost-effective method of generating wind data in lieu of either radar or NAVAID systems. Further work is necessary to evaluate wind profilers. Data from the 50 mHz profiler run by the University College of Wales, Aberystwyth, are being evaluated by the Meteorological Office, and several European countries are also undertaking trials. Much will be learnt from the experience in the United States.

9. The UK observing scenario in 2010 — long-term forecasts

Firstly, there will probably be more observing sites, some possibly only producing one or two parameters with a greater flow of instrumental objective data than at present. This could be achieved using some of the 500 climate stations if they were equipped with low-cost automatic systems. Such data could include visibility, some limited present-weather indicators with cloud height and amount of low cloud. Human observers, if used at all, will be limited to a relatively few stations where full weather and cloud descriptions are still needed, or where required for safe aircraft operation.

Secondly, SYNOPs will not be used for dissemination of observational data within the United Kingdom. Data will come to the centre in basic numerical form in much larger volumes than at present and be redistributed as analyses and short-range predictions. Of course this concept is already being developed for radar data.

Thirdly, SYNOPs if used at all, will be generated only for a limited number of stations and at times needed for broadcast on the Global Telecommunication System. Their generation will be at a central location and not necessarily on site.

Fourthly, upper-air wind-finding by radar with balloon-borne reflectors will have been phased out in favour of NAVAID techniques, using LORAN or GPS or wind profilers. There will be increasing use of aircraft-produced wind data.

Finally, ground-based remote soundings, and aircraft data on the ascent and descent phases, will provide a near-continuous description of temperature distribution with height. Radiosonde flights to provide humidity data and detailed temperature profiles in depth may be made only 12-hourly.

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Quality Assurance in the observations area of the Meteorological Office

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Summary

The Meteorological Office is heavily dependent upon data for service provision. Considerable effort and resources are devoted to maintaining the quality of the data, far exceeding the correction of identifiable errors. This paper describes the overall quality assurance system which has evolved in the observations area of the Meteorological Office.

1. Introduction

The Meteorological Office has much in common with industry in that raw material in the form of observations is taken into the system and subjected to a number of processes leading to the production of a forecast or consultancy service. In the case of forecasts, there is some monitoring against ensuing events which acts as an indicator of quality in absolute terms. There is also considerable feedback from the customer based on a comparison with his perception of what the quality should be. Customer perception of quality is more important in some ways to a service provider than absolute quality. Customer perception is strongly linked with price paid and sales stance. When product improvement operates on a diminishing return, with costs escalating rapidly for small technical gain, it is easy for the actual quality of service to fall far short of the customer's preconceived perception. The inherently variable nature of the weather is such that customers' expectations of weather forecasts cannot always be met.

The problem is rather less critical in the climatological consultancy field as verification is more difficult in the short term and the customer's assessment is more likely

to be made on presentation and fitness of the product for the intended purpose. However, climatological advice can be very sensitive to the quality of data from an individual site, sometimes more so than forecasting products which are based upon numerical models and broader areal analyses.

The Meteorological Office differs from many retailers in that it creates its own raw materials, the data archive, and produces the tools to do this, i.e. the observing instrumentation, the networks, communications and the archiving software. Thus the Meteorological Office must also monitor the quality performance of all the processes affecting the input data.

2. The traditional approach to Quality Assurance

Meteorological observations have been relatively labour intensive until fairly recently, and the quality assurance procedures tend to reflect this situation. Typically, the instruments are designed to measure the atmosphere to specified accuracies and are located in a manner conforming to the best achievable meteorological exposure. The synoptic observer is given a manual of complicated codes designed more for telecommunication convenience than ease of use and is constrained to carry out the whole observing/coding process to tight deadlines. Climatological observing is rather simpler, but those sites reporting on a daily basis via communication lines, rather than in delayed mode in manuscript, still have to deal with codes. It is not surprising that errors do occur, and the Meteorological Office has become very good at detecting and correcting errors in data, having twenty or so staff engaged upon this work.

The advent of automation seems at first sight to have stimulated a different approach, in that most of the problems associated with manual observing, e.g. instrument reading and coding, have been removed. However, automatic observing systems develop faults and monitoring is necessary to initiate repair or replacement action. In severe cases, the data may be deleted until monitoring indicates that the fault has been cleared.

Training and experience are essential parts of quality assurance, and the Meteorological Office has a good record in this respect. Professional observers are trained at the Meteorological Office College early in their careers and attend refresher courses from time to time. The Meteorological Office is fortunate in enjoying the cooperation of a large number of auxiliary and climatological observers who are not professional meteorologists, but who make a major contribution to the observing network. Auxiliary or cooperating observers are encouraged to attend courses. Their observations are monitored by the Meteorological Office station which collects their data, and their observations can be discussed both during collection and the two- to three-yearly inspection visit. Many auxiliaries are being equipped with personal computers which will encode their observations and pass them direct to Bracknell via telephone lines. This will remove the possibility of discussion during collection, but contact between cooperating observers and their professional colleagues is so important that specific meteorological offices are to be made responsible for groups of auxiliaries and will contact them for an informal chat on a regular basis.

The training given to cooperating observers is aimed at encouraging good practice and adherence to standard procedures. The instructors pay special attention to aspects of the work which give rise to difficulty. However, the main objective is to develop observing skills and capitalize upon the interest and dedication of both Meteorological Office and cooperating observers.

3. The concept of Total Quality Assurance

Over the years, the Meteorological Office has developed most of the elements of a Total Quality Assurance programme, but these have yet to be integrated to create a comprehensive system.

The elements are as follows:

(a) Specification of the user requirement for an observing system.
(b) Creation of a technical response.
(c) User field trial, usually preceded by an engineering trial.
(d) Installation for operational use.
(e) Quality evaluation.
(f) Quality control.
(g) Corrective action.
(h) Initiate feedback from user of data.

In what follows, the interrelationships of an integrated and comprehensive system of quality assurance are described. The system is described schematically in Fig. 1.

3.1 The user requirement for an observing system and technical response

The users' requirement should be established by thorough discussion and will be expressed initially as a need for a particular type of data with stated accuracy and resolution. Many users will not state their expectation of reliability or mean time between failures although it is now customary to quote the amount of data which may be lost before a system becomes unacceptable. Often this is expressed in term of the minimum amount of data to be provided, expressed as a percentage of the total possible. Thus a system which is expected to lose no more than 5% of data is said to have a minimum percentage data capture of 95%. However, every user has a preconceived idea of what system performance should be and this must be quantified at this stage. Realism is established and an acceptable target included in the user requirement. The user is likely to base his judgement of satisfaction in terms of quality on whether that target is met.

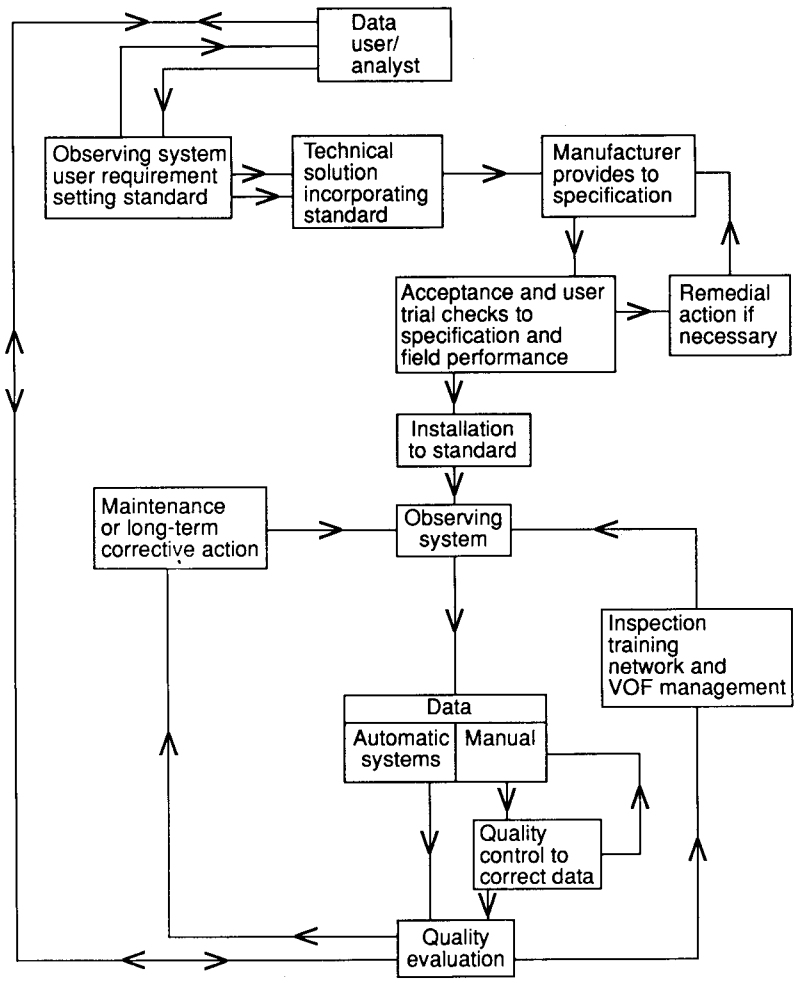

Figure 1. The Total Quality Assurance system.

The technical solution is a response to the user need and should balance what is possible in terms of cost, delivery time, accuracy and performance against the requirement. This is an interactive process leading to an agreed solution. It is vital that the technical specification contains a clear performance target as well as the desired percentage data capture. The time-scale to achieve operational installation should also be agreed at this stage, because the extent to which it is achieved will also affect the users' perception of the quality of the system.

Procurement action is also part of quality assurance because it either helps or prevents the meeting of delivery targets.

3.2 The trial phase

Equipment being tested should meet the technical specification regarding safety, construction and durability. These factors are tested during engineering trials while gaining some evidence of equipment performance and how this matches the users' perception of (agreed) quality.

After the engineering trials, a user trial is set up to determine the performance and reliability of the system under field conditions. For example, a laser cloud-base recorder has been operated at Hemsby, a key operational observing site where there are good data for comparison. Thus the equipment has been evaluated under realistic conditions. Apart from assessing the reliability and performance of the equipment against the original specification, the views of the staff actually using it are canvassed to give an indication of eventual user satisfaction.

3.3 Operational installation

The eventual quality of the data and performance of a system are inevitably related to its operational environment. The quality, effectiveness and durability of the installation are vital if a high rate of failure is to be avoided in operation. Clear and established standards and procedures have evolved as a result of long and hard-won experience. The resulting quality of installation is high and has to meet health, safety and associated legislation.

3.4 Quality evaluation

The function of quality evaluation is to assess the performance of any system by examining the data produced on a routine basis. Any unacceptable features

of performance are investigated to identify the underlying cause and to seek means of eliminating it at source, if this is cost-effective. Errors in individual items of data may be corrected, but this is not an essential part of the work. It is much more important that the errors detected in the data are viewed in the light of insight into the workings of the system. Thus the services of a technician may be requested to carry out essential maintenance work on an automatic system (e.g. Synoptic Automatic Weather Station) and subsequent monitoring will check that the problem is solved. However, if the problem persists, the Quality Evaluation Team must identify this. The cost of continually fixing the system is compared with that of a longer term and permanent technical solution, if one is available. All the Meteorological Office automated observing systems, both on land and at sea, are routinely monitored and evaluated.

With auxiliary observers, the parenting action by professionally manned Meteorological Office stations provides a mix of quality evaluation and quality control, in that errors are also corrected. The professional Meteorological Office staff discuss problems with the observer while collecting the observation. Often these are related to coding but there can be more deeply seated misconceptions regarding observing practice. Parenting stations routinely pass to Bracknell summaries of such problems, so that the staff responsible for inspection and training can target their activities. The introduction of automated data collection resulting from the use of personal computers by auxiliary observers should remove most of the coding errors, leaving only observing errors. This is a major step in quality assurance but, unfortunately, it will also remove the routine contact between parenting station and auxiliary. If quality is to be maintained, a regular contact must be set up to replace the current arrangement. Meteorological Office staff will have to ensure that the auxiliary observer remains fully aware of the value of, and need for, his observations. The contact must not be allowed to relax to 'contact only when errors occur' because this will adversely affect auxiliary observer morale and therefore quality.

Fostering a sense of involvement in the meteorological process is an important step towards Total Quality Assurance. This applies equally to those professionally manned stations established solely to provide observations. Such stations have to be provided with forecast data and other material to maintain interest in the weather and, consequently, in observing standards.

For various data, e.g. from ships, buoys and other platforms, monitoring software within the operational analysis suite of programs produces statistics of errors (Hall 1991). These statistics are analysed and Port Meteorological Officers (PMOs) visit ships to discuss sources of error with observers. Monitoring and quality evaluation is also carried out for upper-air data.

Quality of observations from professionally manned stations is maintained largely by means of a long-established checking system whereby each observer reviews his predecessor's work. More formal objective checking may be introduced later.

It is essential that the quality evaluation manager continues to review the entire observing/data gathering operation to ensure that all possible actions are taken to eliminate sources of error. This involves liaison with staff from the instrument branch, the network managers and inspectorate, and the monitoring team in the Central Forecasting Office.

3.5 Quality control

From its earliest days, the Meteorological Office has always been active in quality control of data, particularly in the areas of climatology and rainfall; some quality control is performed for real-time data entering the Synoptic Data Bank. In general, errors are identified and removed or corrected, sometimes after consultation with the observer. Considerable resources are devoted to this activity, which continues to be developed. For example, a new system is on trial to quality control rainfall data using a personal computer. The gauge totals are compared with radar data and corrections made as required.

The level of quality achieved in the data before presenting them to a user is a matter of agreement and compromise. There should always be some element of user validation, particularly in the case of extreme events. Ideally all the data from any noteworthy event would be subjected to a full and exhaustive spatial and temporal analysis by quality-control staff. This is obviously not practical because of the large volume of data received and the need to approach quality control in a routine and orderly manner. The Meteorological Office does not have sufficient resources to mount detailed investigations. This means that those analysing data from a climatological archive must be satisfied that an agreed standard has been reached in terms of rejection of outliers while attempting to retain climatological extremes. The user should be wary when dealing with extreme cases and discuss doubts and inconsistencies in the data with those responsible for the quality control.

The first priority for quality-control staff is to check and correct the data, and although some effort is made to detect underlying trends or causes, this is a secondary and somewhat *ad hoc* process. Summaries of errors found are passed to the network and inspectorate staff on a monthly basis. This process will be formalized and automated so that it follows quality evaluation principles in trying to eliminate the cause of the problem.

3.6 Corrective action — the role of the Inspectorate

The Meteorological Office has a team of inspectors who visit each auxiliary observing site, climate station and rainfall site approximately every three years. This level of activity conforms to WMO guidelines, and seeks

to ensure that observing practices and instrument exposure meet the accepted standard. Details of errors detected by quality control are available to inspectors visiting climatological and rainfall stations. Auxiliary sites will also be included shortly.

The inspector should discuss the whole process with the observer in detail to establish the individual's *modus operandi* and related ergonomics. The object should be to detect error-prone practices as well as to discuss errors which have actually occurred. All inspectors are well aware of their public relations role, and take great care to commend, encourage and motivate observers.

A number of auxiliary and voluntary climatological observers' training courses are run each year. However, the observers are volunteers and either they or their parent organizations have to fund the time spent on a course. The Meteorological Office pays travel costs and provides accommodation.

The Inspectorate encourages the observers to perform well and this includes attendance on courses. There is no question of compulsion but if a station consistently falls below an acceptable standard it should be discontinued and if a replacement station is required for the network, action taken to identify a suitable candidate. PMOs carry out duties which are broadly similar to those of the station Inspectorate. However, they encounter difficulties in that crew changes are frequent and some UK ships do not enter UK ports at any time. PMOs do offer to visit ships of other nationalities, and bear in mind monitoring results. However, there is little to be done when errors are caused by poor or damaged equipment on board ships of other nationalities. The Meteorological Office can, and does, recruit foreign ships to its voluntary observing fleet, but cannot replace poor equipment on ships from the voluntary observing fleets of other countries.

3.7 Feedback from the users of the data

The user requirement for any observing system reflects the accuracy and performance dictated by the use intended for the data. Quality assurance seeks to maintain the whole data management system to that level of performance. However, it is important that feedback is sought regularly from users of the data to ensure that their perception of the quality achieved matches their expectations and that the expectation matches the level aimed at by the quality-assurance staff. Responsibility for this activity rests with the Quality Assurance Manager.

4. The Management role in Quality Assurance

Management must make it quite clear that there are quality targets and that they will be adhered to at all times. Policies should be determined for data standards as they are for the composition of the various observing networks maintained by the Meteorological Office. Such standards must be defensible when it comes to overall resource allocation. In times of financial stringency it can be all too easy to cut back an apparently non-productive function such as quality assurance. However, the results of doing so with data can have repercussions for future generations. Most companies who have adopted Total Quality Assurance recognize that regulatory systems have a role to play, but largely it is one of reinforcement. Quality will be determined mainly by the attitude of mind of the work force and their pride in producing a worthwhile end result. This means that each member of staff must be encouraged to value their professional contribution.

5. Conclusion

The Meteorological Office is data dependent, and as such the reputation of its products depends upon quality assurance. Standards set must be consistent with the requirement of those producing the highest grade of commercial service, because the same data feed all the services. Maintenance of quality is largely a question of attitudes and management must make it quite clear what is required and stand by that statement. Good communication must be maintained between the various component parts of the data management system with effective feedback on quality, and well coordinated action. The Quality Assurance Manager has a key role to play in this respect. However, none of the regulatory mechanisms will result in a high level of quality unless the members of staff concerned take professional pride in their output, and the value of their contribution is continually emphasized.

Reference

Hall, C.D., Ashcroft, J. and Wright, J.D., 1991: The use of output from a numerical model to monitor the quality of marine surface observation. *Meteorol Mag*, **120**, 137–149.

551.574.42

Rime deposition

W.S. Pike
19 Inholmes Common, Woodlands St Mary, Newbury, Berkshire RG16 7SX

Following two days and nights of freezing fog in a light easterly airflow, the following photographs were taken on 31 January 1992. Fig. 1 shows 2–3 cm of rime deposition as the fog was beginning to clear on the Lambourn Downs. The beech trees showed characteristic translucent or transparent rime on all east-facing twigs, increasing with height above ground level.

Fig. 2 shows the effect of a miniature funnelling of 'upslope' airflow between 'Armco' steel fencing and the ground, leaving transparent rime on the stems of dried grass. Again, depositions of up to 3 cm have occurred where the airflow is strongest.

Fig. 3 shows thin transparent rime on twigs, becoming translucent where thicker accumulations occur at buds. Small trees are on a causeway leading to a narrow bridge over the M4 motorway, standing in an 'upslope' effect as the easterly airflow crosses the embankment.

Fig. 4 is the 'upslope' effect seen in rime depositions on a vertical twig — a close-up of Fig. 3 but viewed (with back light) to the north-east. Rime was transparent and 2–3 cm in length.

Transparent growth occurs when larger fog (or freezing drizzle) droplets strike the obstruction at temperatures just below 0 °C, allowing some 'spreading' of liquid before freezing occurs. Compare these photographs to those of hoar frost (*Meteorol Mag*, **121**, p. 165) which is translucent or opaque white because water vapour (or smaller droplets invisible to the naked eye) were frozen more rapidly on contacting low-level obstructions. The freezing of droplets, or the appearance of crystals, on the edges of blades of grass may challenge the exclusive theory of condensation (as in dew formation) when explaining the appearance of hoar frost crystals.

Perhaps initially hoar frost is 'deposited' by condensation and later the crystals grow by 'accretion' of droplets, similar in essence to rime formation?

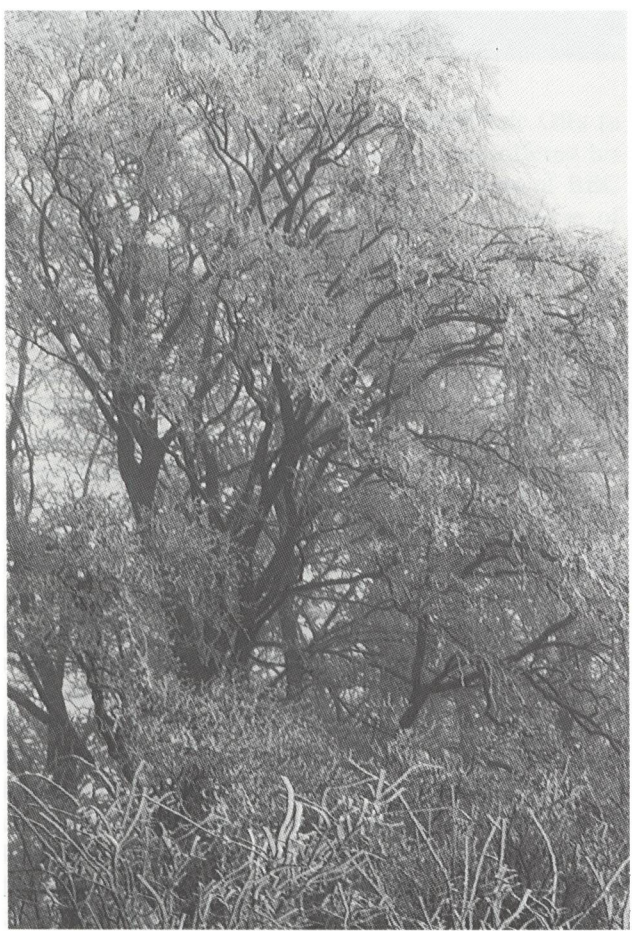

Figure 1. Translucent rime on beech trees on the Lambourn Downs at 1145 UTC.

Figure 2. Rime on grass at 1200 UTC.

Figure 3. Rime deposition on east-facing twigs at 1200 UTC.

Figure 4. Close-up view of Fig. 3.

Reviews

Mountain weather and climate (Second edition), by R.G. Barry. 57 mm × 240 mm, pp. xx+402, *illus.* London, Routledge, 1992. Price £60.00 (hardback), £18.99 (paperback), ISBN 0 415 07112 7, 0 415 07113 5.

It is over ten years since the first edition of this book was published and during that time there have been several important field programmes carried out in mountainous areas, for example, the ALPEX programme. A second edition of this admirable book was therefore long overdue.

The author is a Professor of Geography at the University of Colorado and has had an interest in the mountain world since childhood and his keenness comes through in the text.

Mountain weather and climate is a comprehensive account of our knowledge of the mountain environment. Much of the contents can only be found in scientific reports and magazines which may not be easily available to the general reader. The book is divided into seven sections, each describing a specific topic and accompanied by a detailed list of references, several pages long. The first section provides an introduction to the history of mountain meteorology from the early experiments on the effects of altitude on pressure at the Puy-de-Dôme in 1648 to the design of an Alpine experiment (ALPEX) as part of the Global Atmospheric Research Programme in the 1980s. This is followed by four sections giving more detail on the weather and climate of the mountains, a section on human bioclimatology, weather hazards and pollution and a final section on climatic change. The first five sections are very comprehensive but the final two are quite short. Personally I would have liked to have seen more in the penultimate section on the effects of the mountain environment on the human frame and the expansion of the subsection on weather hazards — avalanches in particular. At the end of the book, beside the general index, the author has provided an additional author index in response to reviews of the first edition.

A book of this kind is obviously expensive. However it is a pity that certain economies appear to have been made. All photographs are in black and white and sometimes are of poor contrast. For example, the first photograph in the book is of the Sonnblick observatory but it is difficult to identify the building against the black sky. Surely it would have been possible to print the photographs in colour. Surprisingly too there are only fifteen photographs throughout the book. This omission is compensated for by the large number of diagrams. In certain cases these could also have been improved by colour, for example, the figures on pages 113 and 114.

The book is really intended to be the definitive reference book on the subject and it performs this task admirably. The reviewer also found it interesting to read but I doubt if many will be of similar mind. The book's cost will mean that few will be willing to buy it in hardback. However, it is a book that any serious library should add to its collection and they should find it more often out on loan than mouldering on their shelves.

T.R. Spalding

Natural weather wisdom, by Uncle Offa (F. Hingston). 142 mm × 221 mm, pp. 160, *illus*. Hanley Swan, Worcester, Image Design and Print Ltd, 1991. Price £9.50. ISBN 185421 146 3.

Once a month since September 1990 Uncle Offa (a *nom de plume* of Frederick Hingston) has offered his natural weather wisdom to Saturday addicts of BBC Radio 4's farming programme, during the course of which he has built up not only a fully paid-up fan club but also, according to the fly of this book, 'an astonishingly high success rate foretelling the weather "according to the ancients" '. So how does he, and others professing similar expertise, do it? What signs do the experts use and which do they ignore? I approached this book in anticipation hoping to discover the secrets of using swallows, frog spawn and St. Swithin's Day for weather prediction in both the long and the short term, to be able to anticipate cold winters, sunny summers and late frosts and to become a sage in forecasting next year's crop yields. Was I satisfied; do I feel I have gained the knowledge basic to the countryman's lore? Well, no, not really. Uncle Offa retains a few of his secrets.

In fewer than 150 pages of widely spaced text, liberally interspersed with pleasant line drawings, Uncle Offa presents a large number of basic prediction rules, for short-, medium- and long-term forecasts. In the first chapter he deals with the 'Days of Prediction', days known to the Druids on which weather patterns for the forthcoming few weeks are set (*As the wind is on St. Michael's Day so 't' will be for three months*). St. Swithin's Day is the best known Day of Prediction. The moon's links to the weather are dealt with in chapter 2 (*it will be a wet month that has two full moons in it*). The next three chapters cover various 'Monthly signs', mainly sayings which relate to predictions of winter (*if in October the leaves still hold, the coming winter will be cold*) and, bearing in mind the country origins of this wisdom, summer (*a green Christmas brings a good harvest next year*). 'Signs of rain', or chapter 6, not only has "*Red sky at night....*" but also "*when eager bites the thirsty flea clouds and rain you'll surely see*". Birds (*in Richmondshire, some persons say that the breastbone of ducks after being cooked are observed to be dark-coloured before a severe winter and much lighter-coloured before a mild winter*) and miscellaneous matters (*when lobsters end the crawling season early, there will be an early winter*) form the subject matter of the next two chapters. Throughout all of this Uncle Offa identifies lores he considers either particularly reliable or probably questionable (I leave it to the reader to decide into which categories the above samples fall); in most cases, however, no comment is passed.

Finally, chapter 9 promises to put it all together. I started this chapter in expectation, I ended it in disappointment. I must learn to recognize those signs of local significance, although giving precedence to the Days of Prediction, then the phases of the moon and then the monthly signs. How do I put it all together? Concentration, observation and persistence. No cook book here, I'm afraid. But I was forewarned: 'forecasting by weather signs is a very local business and the signs are unlikely to give a true reading beyond the confines of the parish'.

And how accurate is it? Uncle Offa claims 85% (whatever that means). Tim Finney, editor of the BBC farming programme, admits in his introduction to the book to having created a deafening silence on air by asking this question. There is a book, *Red sky at night, shepherd's delight? Weather lore of the English countryside* (Sheba Books) by P.J. Marriott, in which some attempt is made to validate similar saws. I spot-checked a large number of Uncle Offa's sayings against verifications in Marriott's book. Results were mixed, with few of those sayings I checked having validity according to Marriott. I should also note that Duncan (*Weather*, **46**, 377–383) expresses caution about the value of long-term prediction saws from north of the border.

So, would any reader wish to make a careful analysis of Uncle Offa's radio predictions? I doubt it. The ways of the countryside have been handed down generation to generation and are part of our natural heritage. We would be the poorer were scientific incredulity to interpose upon this culture. This is not the only book on this subject, but it is one of the easier ones to read. Uncle Offa's fan club members will no doubt purchase it with glee. But how many of them will admit to making hard decisions on the basis of Uncle Offa's predictions?

M.S.J. Harrison

The engineering statistician's guide to continuous bivariate distributions, by T.P. Hutchinson and C.D.Lai. 143 mm × 206 mm, pp. xxii+246, *illus.* Adelaide, Rumsby Scientific Publishing. Price $A44.00, $US32.00. ISBN 0 646 024132.

As the title implies, Hutchinson and Lai's book is concerned with continuous bivariate distributions and the emphasis is very much on the distributions themselves and not on related matters such as statistical tests or statistical modelling. Bivariate distributions have a much greater range of possible forms than univariate distributions, and a large part of this book is devoted to presenting examples of this rich variety. The examples in the book arise in various ways such as mixing and compounding of simpler distributions, transformation of other multi-dimensional random variables, series expansions for the distribution functions, and the combination of a marginal distribution and a given set of conditional distributions. One of the recurring themes of the book is the idea of separating the study of the relationship between the two variables in question from the study of the univariate marginal distributions. This is achieved by separately transforming the two variables so that their marginal distributions have a standard form (usually uniform, normal or exponential). The book also contains discussions of reliability (e.g. how does the failure rate of a component depend on its age?) in the bivariate context, ways of measuring the degree of dependence and correlation between two variables, and techniques for generating pairs of random numbers with various distributions. Many applications are mentioned (including several meteorological examples) but in most cases these are dealt with rather briefly.

The book is to be welcomed as it brings together information which is not readily accessible outside of journal articles and conference proceedings. It has an extensive list of references which provide a good starting point for someone who wants to 'get into' the subject and it also has a good, if somewhat unusual, index (some of the sub items listed under one heading are so numerous that one loses track of which 'level' of the index one is looking through). However, the contents of the book give the impression of a loose collection of facts rather than a well-developed theory. Although this is partly a consequence of the nature of the subject, it is in places taken to the extreme. Many ideas are only given as references 'X did such and such while Y did so and so' and in a few places details of the figures and chapters from other books are listed. I also found the lack of theory in the book rather disappointing. In reading the book I found questions kept occurring to me to which the book provided no answers. For example, in discussing bivariate extreme-value distributions, the marginal distributions are transformed to a particular extreme-value form without discussing whether this preserves the bivariate extreme-value property. Also a number of concepts and distributions are presented with little probabilistic motivation.

The book is well produced with good quality text and mathematical typesetting. There are a number of errors and the meaning is not always as clear as one would like (for instance in discussing extreme-value distributions the authors say careful attention is needed as to whether one is dealing with maxima or minima — however they fail in most of their discussions to say which they are considering). However, these errors and lack of clarity are not a serious problem — it is usually possible with a little thought to see what's going on. There are also one or two oddities in the ordering of the book, with concepts being introduced after they have been used, but again these are not a significant hindrance to understanding.

Despite the above criticisms, the book fills a useful role. It would be an appropriate starting point for someone with a reasonable background in statistics who wishes to learn about different types of bivariate distribution.

D.J. Thomson

GUIDE TO AUTHORS

Content

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Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (IBM-compatible) can be labour-saving, but only a print-out should be submitted in the first instance.

References should be made using the Harvard system (author/date) and full details should be given at the end of the text. If a document is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to, except by 'personal communication'.

Tables should be numbered consecutively using roman numerals and provided with headings.

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and read. Notation should be kept as simple as possible. Guidance is given in BS 1991: Part 1: 1976, and *Quantities, Units and Symbols* published by the Royal Society. SI units, or units approved by the World Meteorological Organization, should be used.

Articles for publication and all other communications for the Editor should be addressed to: The Chief Executive, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ and marked 'For Meteorological Magazine'.

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